BARIUM CLOUDS IN SPACE

- ionosphere release
  - structure
  - skidding
- magnetospheric release: Hall MHD
OPTICAL MEASUREMENTS OF LASL
OPERATION AVEFRIA BARIUM SHAPED
CHARGE RELEASE PHENOMENOLOGY

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BARIUM CLOUD STRUCTURE
Avefria Dos - This release was at Tonopah, Nevada in May 1978 (Pongrantz et al.) at an altitude of about 190 km. The view is from Hot Creek Valley, Nevada about three minutes after the release. This was a 1.45 kg shaped charged barium release fired across the magnetic field. The barium cloud had an initial radius of about 1 km. The "cats paw" part of the figure is looking up the magnetic field line, and the longer part of the cloud is not up the field line.


growth rate:

\[ \gamma = \frac{V}{L_n} \quad \text{collisional limit} \]

\[ \gamma = (v_{in} V / L_n)^{1/2} \quad \text{collisionless limit} \]
\[
\Sigma(x, y) = \int \sigma_p(x, y, z) \, dz \quad \text{(barium conductance)}
\]

\[
\frac{\partial \Sigma}{\partial t} = -\nabla \cdot (\Sigma \mathbf{V}) \quad \text{where} \quad \mathbf{V} = -\frac{c}{B} \nabla \phi \times \mathbf{e}_z
\]

\[
\nabla \cdot (\Sigma \nabla \phi) = \frac{B}{c} \mathbf{V}_n \cdot \nabla \Sigma
\]

\[M = \frac{\Sigma_{max}}{\Sigma} \quad \text{cloud ‘strength’}\]
NUMERICAL SIMULATION RESULTS
from McDonald et al. (1980)
SIMULATION VS ANALYTIC THEORY
from McDonald et al. (1980)
BARIUM CLOUD

$M = 2$
M2/M10 COMPARISON

M2 faster than M10
SIMULATION VS ANALYTIC THEORY

from McDonald et al. (1980)
- solve continuity, velocity, temperature equations
- ions: $\text{H}^+, \text{O}^+, \text{He}^+, \text{N}^+, \text{N}_2^+, \text{NO}^+, \text{O}_2^+$
  - added Ba$^+$
- full transport for all ions
- interhemispheric model
- vertical and zonal $E \times B$ drift
  - obtained from solution of potential equation
- ambient neutral species: NRLMSISE00/HWM93
- fully parallelized (MPI)
- nonorthogonal, nonuniform fixed grid
SCHEMATIC OF CLOUD ELECTRODYNAMICS

'Skidding'
based on CRRES G-9 study (Huba et al., *GRL* 19, 1085, 1992) and ESF study (Huba et al., *GRL* 35, L010102, 2008)

neutral barium cloud evolution

\[
N_{Ba} = \frac{(1 - \epsilon)N_0 e^{-\sigma_i t}}{(\pi)^{3/2} v_{th}^3 t^3} \exp \left[ -\frac{(x - x_0 - V_{n0}t)^2 + (y - y_0)^2 + (z - z_0)^2}{v_{th}^2 t^2} \right]
\]

barium ionization rate \( \sigma_i = 0.0357 \)
• ion continuity equation

\[
\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{V}_i) = P_i - L_i n_i
\]

• ion velocity equation

\[
\frac{\partial \mathbf{V}_\alpha}{\partial t} + (\mathbf{V}_\alpha \cdot \nabla) \mathbf{V}_\alpha = -\frac{1}{\rho_\alpha} \nabla P_\alpha + \frac{e_\alpha}{m_\alpha} \mathbf{E} + \frac{e_\alpha}{m_\alpha c} \mathbf{V}_\alpha \times \mathbf{B} + \mathbf{g}
\]

\[
-\nu_{\alpha n} \mathbf{V}_\alpha - \sum_j \nu_{\alpha j} (\mathbf{V}_\alpha - \mathbf{V}_j)
\]

\[
-\frac{\sigma_{i n}}{n_i} (\mathbf{V}_i - \mathbf{V}_{n0}) \quad \text{barium ion source}
\]
POTENTIAL EQUATION based on current conservation: $\nabla \cdot J = \nabla \cdot (\Sigma_{Pc} + \Sigma_{Pi}) \nabla \phi = -\nabla \cdot \Sigma_{Ps} \begin{pmatrix} \nabla \phi - \frac{B}{c} V_{n0} \times e_z \end{pmatrix}

\Sigma_{Pi} = \int \sum_j (ce/B)(n_j \nu_{jn}/\Omega_j) \, dz

\Sigma_{Pc} = \int (ce/B)(n_c \nu_{cn}/\Omega_c) \, dz

\Sigma_{Ps} = \int (ce/B)(n_n \sigma_i/\Omega_c) \, dz

- \textit{i}: background ionosphere
- \textit{c}: barium ion cloud
- $N_{Ba} = 10^{27}$ (barium neutrals)
- $V_{n0} = 10$ km/s (injection velocity)
- $v_{th} = 1.5$ km/s (expansion velocity)
- $F10.7 = 170$ (solar flux)
- LT = 0630 (morning)
- $t_0 = 80$ s (1 min run time)
- geometry: longitudinal wedge 12° ($L = 1380$ km)
RESULTS 1

barium ion isosurfaces

$t = 0 \text{ s}$

$t = 46 \text{ s}$
RESULTS 1

barium ion isosurfaces
RESULTS 2

density and potential contours
RESULTS 3

density and velocity plots

10 s intervals

Ba⁺ density (cm⁻³)

Ba⁺ velocity (m/s)
cloud skidding and Alfvén waves

- **skidding**
  - maximum \( E \times B \) velocity: \( V_{skid} \approx 200 \, \text{m/s} \), i.e., very little skidding
  - velocity scales as
    \[
    V_{skid} \approx \frac{\Sigma_{ps}}{\Sigma_{pb} + \Sigma_{pc} + \Sigma_{ps}} \quad V_{n0} \approx 0.05 \quad V_{n0} \approx 500 \, \text{m/s}
    \]
  
- energy loss: \((1/2)M_{Ba}V_{skid}^2 \approx 5 \, \text{MJ}\)

- **Alfvén wave propagation**
  - Alfvén velocity: \( V_A \approx 10^3 \, \text{km/s} \)
  - field line length to \( E \) region: \( L \approx 3 \times 10^3 \, \text{km} \)
  - transit time: \( \approx 3 \, \text{s} \ll 30 \, \text{s} \) (ionization time)
  - assume complete coupling to \( E \) region
• rapid structure formation: \[ t < \Omega_i^{-1} \]

• small scale structure: \[ \lambda < \rho_i \]
HALL MHD: SUB-ALFVÉNIC EXPANSIONS
laser-plasma interaction (Ripin et al., PRL, 1987)
HALL MHD: SUB-ALFVÉNIC EXPANSIONS
theory (Hassam and Huba, GRL, 1987)

- dispersion equation

\[
\frac{\omega^4}{k^2 V_A^2} - (1 + \beta)\omega^2 + (g/L_n)(1 - \partial \ln B / \partial \ln n) - \left(\frac{\rho_i}{L_n}\right)(\omega^2 - k^2 gL_n) \left(\frac{\omega}{kC_s}\right) = 0
\]

where \( g = -\frac{dV_0}{dt} \)

- limiting cases for the growth rate:

\[
\gamma = \left(\frac{g}{L_n}\right)^{1/2} \quad \rho_i << L_n
\]

\[
\gamma = k L_n \left(\frac{g}{L_n}\right)^{1/2} \quad \rho_i >> L_n
\]
HALL MHD: SUB-ALFVÉNIC EXPANSIONS

simulation study (Huba et al., JGR, 1992)
HALL MHD: SUB-ALFVÉNIC EXPANSIONS

psychedelic perspective